

LA-UR-01-3639

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Title:

Using A Probabilistic Knowledge Base To Predict Failure And Validate Numerical Simulations

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Submitted to:

<http://lib-www.lanl.gov/la-pubs/00796635.pdf>

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Using A Probabilistic Knowledge Base To Predict Failure And Validate Numerical Simulations

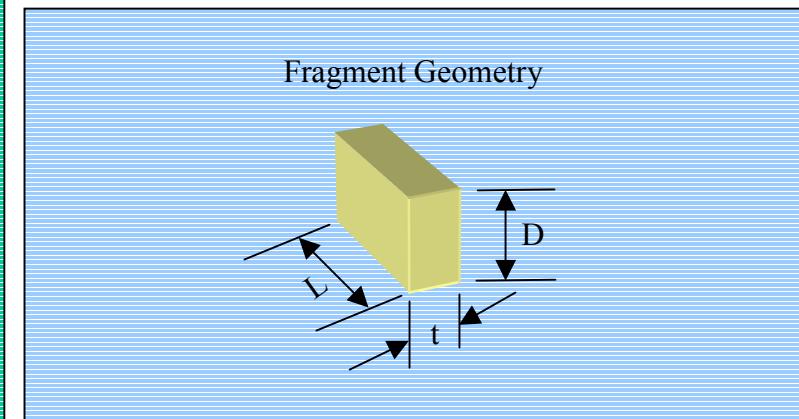
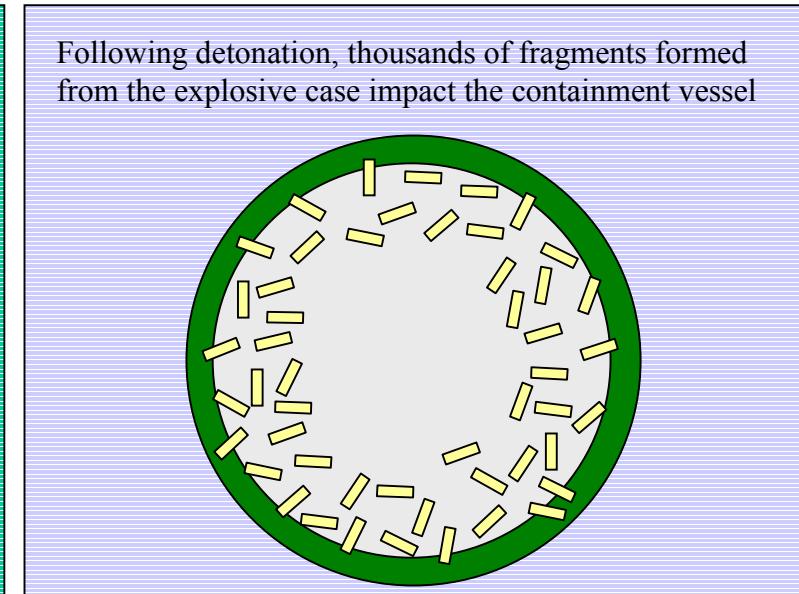
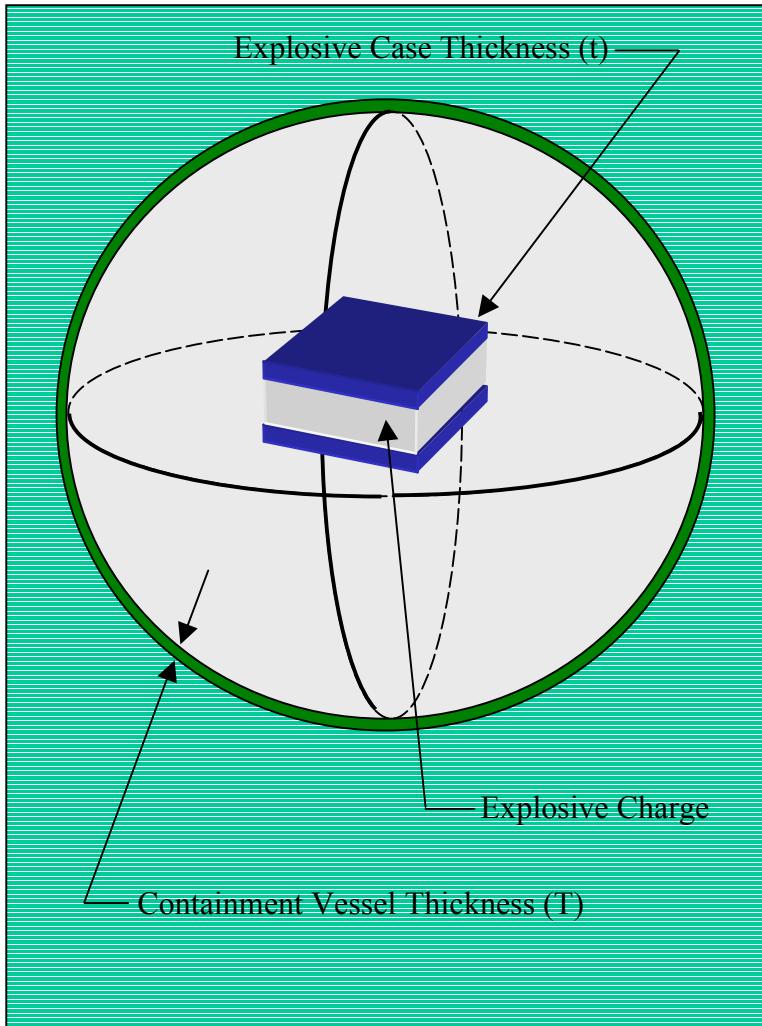
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667-9142

Schematic of DynEx Containment Vessel Test



Probability Analysis

Using the results from previous tests along with experimentally derived theories the probability a single fragment penetrates beyond a given target depth is made.

Inherent in the analysis is the likelihood specific event scenarios occur.

Metrics for Three Test Scenarios

Failure occurs when a fragment,

1. penetrates beyond 1" of material (thickness of the old containment vessel and half the thickness of the new design).
2. penetrate beyond 2" of material (thickness of the new containment vessel design).
3. penetrate beyond 5.25" of material (thickness of the new containment vessel design plus the safety vessel thickness).

Two Modeling Approaches Used to Assess a Fragment's Probability of Perforation

1. **Likelihood of Occurrence Model:** Entire DynEx test modeled as a single event.

2. **Stochastic Sampling Model:** Each random fragment taken as an event.

Propagating Uncertainty

Use theoretical and experimental evidence to define **probable** values for key parameters.

- 1. Geometry:** Fragment geometry is distributed. Key parameters include fragment mass (m_f), diameter (D), and ratio of length to diameter (L/D). Need estimates for $P(m_f)$, $P(D)$, and $P(L/D|D)$.
- 2. Orientation:** Fragment orientation is random. Want to know probability a fragment is within some critical $\pm\alpha$ angle. $\Rightarrow P(\alpha)$.
- 3. Velocity:** Fragments must obtain a geometry dependent critical velocity for perforation to occur. The probability is $\Rightarrow P(>v_{cr})$.

Probabilistic Formulation

A fragment's probability of perforation $P(p)$, depends on

1. Probability a large enough fragment exists,
2. Probability fragment travels fast enough for its L/D and L/P ratios, and
3. Probability fragment is within its critical orientation.

This is expressed as

$$P(p) = P(\text{big enough}) * P(\text{right geometry}) * P(\text{fast enough}) * P(\text{right orientation})$$

Mathematically this becomes

$$\begin{aligned} P(p) &= P(m_f) * P(G_f) * P(v_f > v_{cr}) * P(\alpha) \\ &= \left(\frac{2\alpha}{\pi} \right) * P(m_f) * P(L_D | D) * P(D) * P(v_f > v_{cr}) \end{aligned}$$

Probabilistic Formulation for Discrete Cases

For given sets of discrete fragment diameters and (L/D) ratios the probabilistic formulation becomes

$$\begin{aligned} P(\text{failure}) &= \sum_{i=1}^N P_i(\text{perforation}) \\ &= \left\{ \frac{2\alpha \cdot m_{\text{case}}}{\pi \sum_{i=1}^N P(m_i)} \right\} \cdot \sum_{i=1}^n \left\{ \left[\frac{P(m_i)}{m_i} \right] \cdot P(L_i/D_i | D_i) \cdot P(D_i) \cdot P(v_{i(\text{fragment})} > v_{i(\text{cr})}) \right\} \end{aligned}$$

where

$\sum_{i=1}^N P_i(\text{perforation})$ = Sum of all the discrete probabilities of perforation

m_{case} = Mass of the explosive case

m_i = Mass of a fragment with the i th discrete set of conditions

$P(m_i)$ = Probability a fragment with mass m_i exists

$\sum_{i=1}^N P(m_i)$ = Sum of all the discrete mass probabilities

$P(D_i)$ = Probability a fragment with the i th discrete diameter exists

P(failure) for the Likelihood of Occurrence Model

For each mutually exclusive fragment event, Bayes' Rule can be used to express the net P(failure).

$e_i \equiv$ The event "fragment i occurs"

$p \equiv$ The event "fragment perforates target thickness"

then

$L(ei)$ \equiv The likelihood i th fragment occurs.

$P(p|ei)$ \equiv Probability i th fragment perforates target thickness given it occurs.

Applying the rule of elimination

$$P(p \cap ei) = L(ei) \cdot P(p|ei)$$

and

$$\begin{aligned} P(\text{failure}) &= P(p \cap e_1) + P(p \cap e_2) + \dots + P(p \cap e_{nf}) \\ &= L(e_1) \cdot P(p|e_1) + L(e_2) \cdot P(p|e_2) + \dots + L(e_{nf}) \cdot P(p|e_{nf}) \end{aligned}$$

Likelihood of Occurrence Model continued

$$P(\text{failure}) = \sum_{i=1}^N P_i(\text{perforation}) = \sum_{i=1}^{nf} L(e_i) \cdot P(p|e_i)$$

Where,

N = number of discrete fragment events, i.e., #bins

nf = total number of fragments that exists.

$$\begin{aligned} P(\text{failure}) &= \sum_{i=1}^N P_i(\text{perforation}) \\ &= \left\{ \frac{2\alpha \cdot m_{case}}{\pi \sum_{i=1}^N P(m_i)} \right\} \cdot \sum_{i=1}^n \left\{ \left[\frac{P(m_i)}{m_i} \right] \cdot P(L_i/D_i | D_i) \cdot P(D_i) \cdot P(v_{i(fragment)} > v_{i(cr)}) \right\} \end{aligned}$$

P(failure) for the Stochastic Sampling Model

For each random and independent event the P(perforation) is

$$P(\text{perforation}) = \left(\frac{2\alpha}{\pi} \right) * P(m_f) * P(\text{✓}_D | D) * P(D) * P(v_f > v_{cr})$$

Given N fragment events each having some P(perforation), the probability of failure is

$$P(\text{failure}) = F[P_i(\text{perforation})]_{i=1,\dots,N}$$

The three measures of failure used were,

1. Worst Probable Point (WPP)
2. 95% Confidence Band
3. Sample μ and σ

Continuous assessment of the likelihood a fragment penetrates/perforates a containment vessel during a DynEx explosive experiment.

INPUT Parameters

Fragment Density	(g/cm ³)	17.69
Fragment Thickness	(cm)	0.5
Fragment Cone Angle	(deg)	20.00
Target Thickness	(cm)	5.08

Mass Distribution	<input type="button" value="Edit Table"/>
Velocity Distribution	<input type="button" value="Edit Table"/>

Logical Model

Click
to view

OUTPUT Parameters

P(mass)	<input type="button" value="Calc"/>	
P(velocity)	<input type="button" value="Calc"/>	

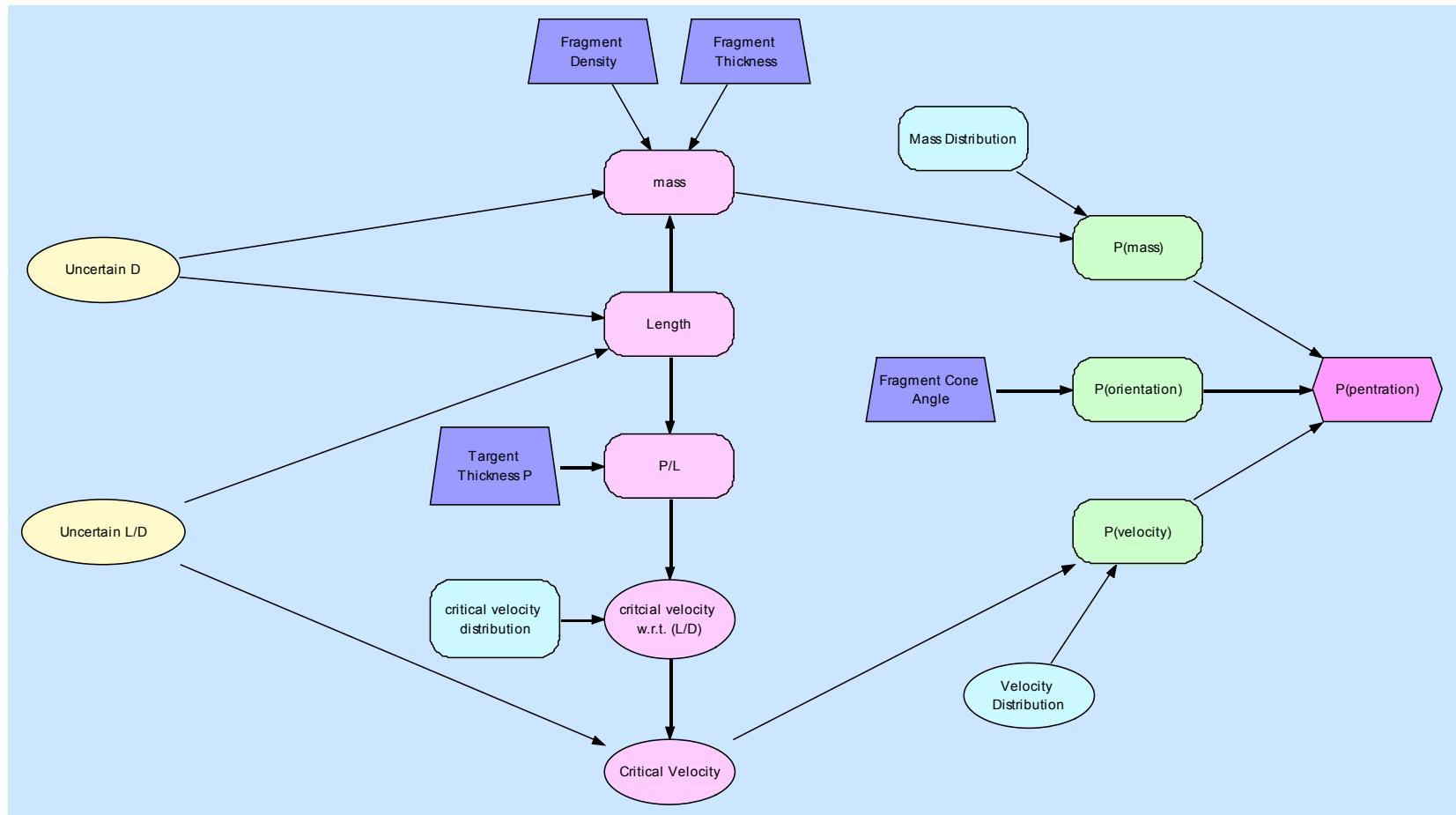
Uncertain Parameters

Diameter Distribution	<input type="button" value="Beta"/>	
(L/D) Ratio Distribution	<input type="button" value="Beta"/>	

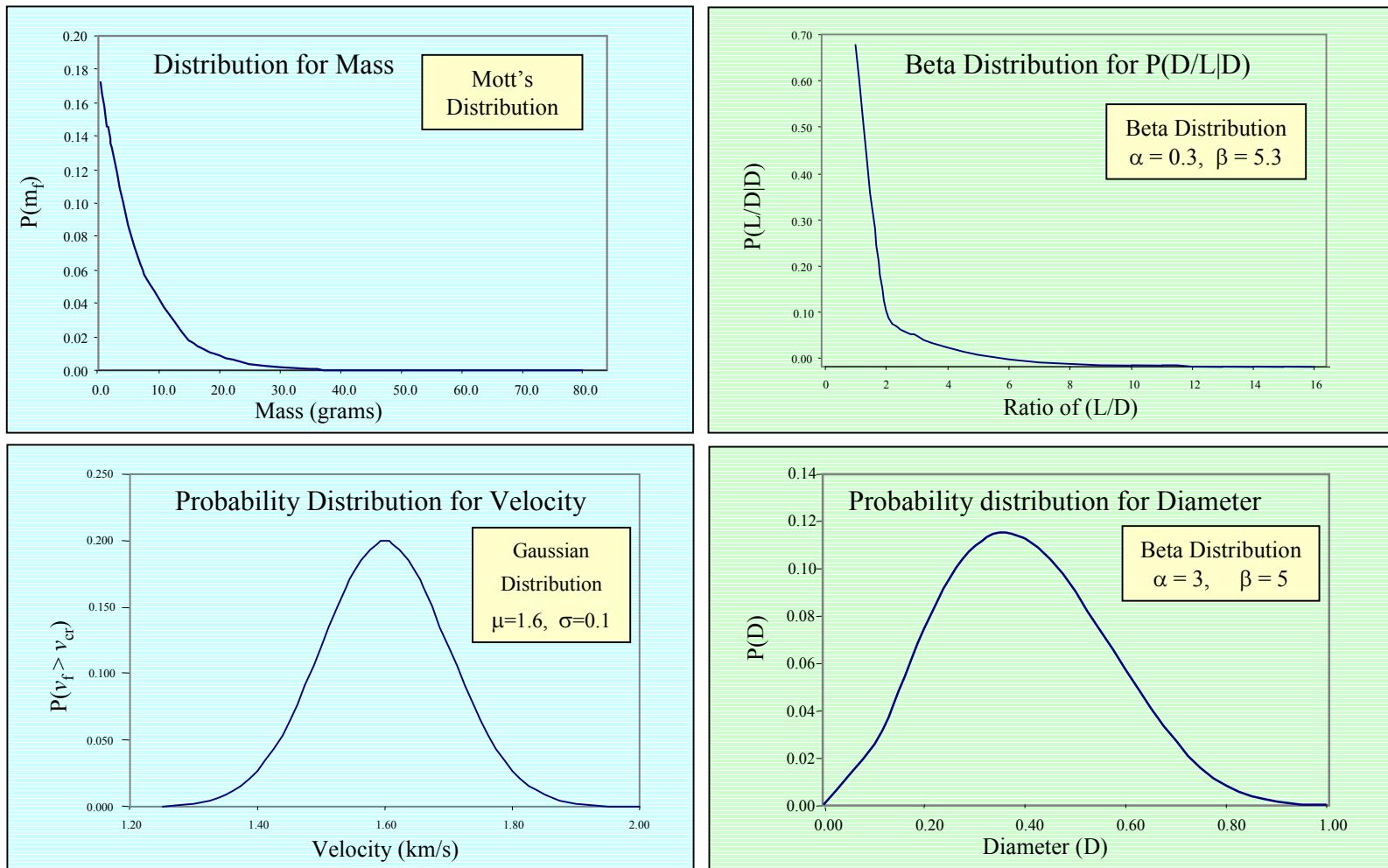
Analysis Results

P(penetration)	<input type="button" value="Calc"/>	
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Influence Diagram for the Continuous Probabilistic Assessment Model



Parameter Distributions



Results for Scenario Simulations

Containment Vessel Thickness	Probability of Failure		
	Likelihood of Occurrence Simulation $P(\text{perforation})$	Stochastic Sampling Simulation's Worst Probable Point	Performance Requirements
	1"	8.90E-03	2.20E-03
	2"	1.52E-05	1.55E-04
5.25"		1.23E-13	2.50E-09

Assessing Margin and Safety

Margin for Likelihood of Occurrence Simulation

	Upper Specification Limit (USL)	μ of Sampled Fragment Events	σ of Sampled Fragment Events	Capabilitiy Ratio (Cp)	% of Specification
Vessel Thickness	1"	1.00E-06	2.22E-04	-0.10	-968.202
	2"	1.00E-06	3.81E-07	0.14	724.040
	5.25"	1.00E-09	3.08E-15	19963.74	0.005

Margin for Stochastic Sampling Simulation

	Upper Specification Limit (USL)	μ of Sampled Fragment Events	σ of Sampled Fragment Events	Capability Ratio (Cp)	% of Specification
Vessel Thickness	1"	1.00E-06	1.38E-05	-0.083	-1197.89
	2"	1.00E-06	3.72E-07	0.038	2648.89
	5.25"	1.00E-09	2.10E-13	7.823	12.78

Safety Index

Simulation Type	Model	Target Safety Index	Computed Safety Index	Outcome
Likelihood of Occurrence	1"	4.75	2.37	CV by itself is Unsafe
	2"	4.75	4.69	CV by itself is slightly Unsafe
	5.25"	5.998	7.32	2" CV + SF is SAFE
Stochastic Sampling	1"	4.75	2.85	CV by itself is Unsafe
	2"	4.75	3.61	CV by itself is Unsafe
	5.25"	5.998	5.85	2" CV + SF is slightly Unsafe

Likelihood of Occurrence Probability Assessments

Vessel Thickness		L / D									
		1	3	4	6	7	8	10	12	14	16
P = 1in		1	3	4	6	7	8	10	12	14	16
D	0.250	0	0	0	0	0	2.53E-07	1.41E-04	1.28E-04	2.60E-05	6.65E-06
	0.500	0	3.74E-03	2.08E-03	1.65E-03	2.58E-04	2.21E-05	1.01E-05	3.51E-07	7.22E-08	2.63E-09
	0.750	0	7.47E-04	4.43E-05	2.47E-06	9.32E-07	6.49E-08	1.78E-08	6.18E-10	1.27E-10	4.63E-12
	1.000	0	5.86E-07	2.52E-08	8.39E-10	3.16E-10	2.20E-11	6.04E-12	1.68E-13	4.31E-15	1.57E-16

Vessel Thickness		L / D									
		1	3	4	6	7	8	10	12	14	16
P = 2in		1	3	4	6	7	8	10	12	14	16
D	0.250	0	0	0	0	0	0.00E+00	0.00E+00	0.00E+00	1.05E-15	8.98E-09
	0.500	0	0.00E+00	0.00E+00	0.00E+00	9.20E-18	6.70E-06	6.86E-06	3.37E-07	7.04E-08	2.58E-09
	0.750	0	0.00E+00	4.40E-14	3.92E-07	7.84E-07	6.45E-08	1.78E-08	6.18E-10	1.27E-10	4.63E-12
	1.000	0	2.37E-17	7.77E-09	8.34E-10	3.16E-10	2.20E-11	6.04E-12	1.68E-13	4.31E-15	1.57E-16

Vessel Thickness		L / D									
		1	3	4	6	7	8	10	12	14	16
P = 5.25in		1	3	4	6	7	8	10	12	14	16
D	0.250	0	0	0	0	0	0.00E+00	0.00E+00	0.00E+00	1.05E-15	0.00E+00
	0.500	0	0.00E+00								
	0.750	0	0.00E+00	4.03E-15	1.05E-13						
	1.000	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.98E-21	1.12E-14	1.33E-15	7.86E-17

Numerically Predicted Failure
Numerically Predicted Success
No Numerical Prediction

Numerical Assessments

PENETRATION PARAMETERS FOR U6NB FRAGMENTS IMPACTING A 2-INCH THICK HSLA-100 STEEL PLATE.
THE RESIDUAL EXIT VELOCITY OF ORIGINAL FRAGMENT IS SHOWN.

Radius (cm)	Diameter (cm)	Length (cm)	Mass (g)	L/D Ratio	Velocity (km/s)	Depth of Penetration (cm)	P/L Ratio	Residual Velocity (km/s)	Residual Length (cm)	REMARKS
0.5	1	1	13.67	1	2	2.104	2.104	0.000	0.143	
0.5	1	2	27.33	2	2	4.186	2.093	0.000	0.143	
0.5	1	3	41.00	3	2			0.788	0.170	Perforated
0.5	1	4	54.66	4	2			1.614	0.567	Perforated
0.5	1	5	68.33	5	2			1.802	1.480	Perforated
0.5	1	6	82.00	6	2			1.864	2.453	Perforated
0.5	1	7	95.66	7	2			1.896	3.439	Perforated
0.5	1	8	109.33	8	2			1.916	4.431	Perforated
0.5	1	1	13.67	1	1.75	1.734	1.734	0.000	0.154	
0.5	1	2	27.33	2	1.75	3.390	1.695	0.000	0.162	
0.5	1	3	41.00	3	1.75			0.318	0.191	Perforated
0.5	1	4	54.66	4	1.75			1.221	0.475	Perforated
0.5	1	5	68.33	5	1.75			1.504	1.310	Perforated
0.5	1	6	82.00	6	1.75			1.586	2.270	Perforated
0.5	1	7	95.66	7	1.75			1.627	3.251	Perforated
0.5	1	8	109.33	8	1.75			1.651	4.240	Perforated
0.5	1	1	13.67	1	1.5	1.402	1.402	0.000	0.174	
0.5	1	2	27.33	2	1.5	2.728	1.364	0.000	0.191	
0.5	1	3	41.00	3	1.5	4.645	1.548	0.000	0.221	Perforated
0.5	1	4	54.66	4	1.5			0.773	0.402	Perforated
0.5	1	5	68.33	5	1.5			1.167	1.080	Perforated
0.5	1	6	82.00	6	1.5			1.290	2.003	Perforated
0.5	1	7	95.66	7	1.5			1.345	2.970	Perforated
0.5	1	8	109.33	8	1.5			1.376	3.951	Perforated

Data from BREAKOUT 2D code by J. D. Walker and C. E. Anderson, SwRI.

NOTE: ORANGE boxes show exceed the mass limit of fragments.

Numerical Assessments

PENETRATION PARAMETERS FOR U6NB FRAGMENTS IMPACTING A 2-INCH THICK HSLA-100 STEEL PLATE.
THE RESIDUAL EXIT VELOCITY OF ORIGINAL FRAGMENT IS SHOWN.

Radius (cm)	Diameter (cm)	Length (cm)	Mass (g)	L/D Ratio	Velocity (km/s)	Depth of Penetration (cm)	P/L Ratio	Residual Velocity (km/s)	Residual Length (cm)	REMARKS
0.375	0.75	0.75	5.77	1	2	1.353	1.804	0.000	0.108	
0.375	0.75	1.5	11.53	2	2	2.428	1.618	0.000	0.108	
0.375	0.75	2.25	17.30	3	2	4.430	1.969	0.000	0.111	
0.375	0.75	3	23.06	4	2			0.770	0.126	Perforated
0.375	0.75	3.75	28.83	5	2			1.393	0.264	Perforated
0.375	0.75	4.5	34.59	6	2			1.732	0.884	Perforated
0.375	0.75	5.25	40.36	7	2			1.822	1.605	Perforated
0.375	0.75	6	46.12	8	2			1.865	2.342	Perforated
0.375	0.75	0.75	5.77	1	1.75	1.141	1.521	0.000	0.117	
0.375	0.75	1.5	11.53	2	1.75	2.094	1.396	0.000	0.122	
0.375	0.75	2.25	17.30	3	1.75	3.198	1.421	0.000	0.127	
0.375	0.75	3	23.06	4	1.75	4.827	1.609	0.000	0.138	
0.375	0.75	3.75	28.83	5	1.75			0.894	0.225	Perforated
0.375	0.75	4.5	34.59	6	1.75			1.389	0.692	Perforated
0.375	0.75	5.25	40.36	7	1.75			1.526	1.390	Perforated
0.375	0.75	6	46.12	8	1.75			1.585	2.121	Perforated
0.375	0.75	0.75	5.77	1	1.5	0.933	1.244	0.000	0.134	
0.375	0.75	1.5	11.53	2	1.5	1.742	1.161	0.000	0.146	
0.375	0.75	2.25	17.30	3	1.5	2.629	1.168	0.000	0.155	
0.375	0.75	3	23.06	4	1.5	3.703	1.234	0.000	0.165	
0.375	0.75	3.75	28.83	5	1.5	5.530	1.475	0.000	0.204	Bulging
0.375	0.75	4.5	34.59	6	1.5			0.924	0.453	Perforated
0.375	0.75	5.25	40.36	7	1.5			1.187	1.067	Perforated
0.375	0.75	6	46.12	8	1.5			1.281	1.777	Perforated

Data from BREAKOUT 2D code by J. D. Walker and C. E. Anderson, SwRI.

NOTE: ORANGE boxes show exceed the mass limit of fragments.

Numerical Assessments

Radius (cm)	Diameter (cm)	Length (cm)	Mass (g)	L/D Ratio	Velocity (km/s)	Depth of Penetration (cm)	P/L Ratio	Residual Velocity (km/s)	Residual Length (cm)	REMARKS
0.25	0.5	0.5	1.71	1	2	0.827	1.653	0.000	0.070	
0.25	0.5	1	3.42	2	2	1.459	1.459	0.000	0.072	
0.25	0.5	1.5	5.12	3	2	2.114	1.409	0.000	0.075	
0.25	0.5	2	6.83	4	2	2.798	1.399	0.000	0.077	
0.25	0.5	2.5	8.54	5	2	3.564	1.426	0.000	0.079	
0.25	0.5	3	10.25	6	2	4.609	1.536	0.000	0.080	
0.25	0.5	3.5	11.96	7	2			0.752	0.098	Perforated
0.25	0.5	4	13.67	8	2			1.526	0.303	Perforated
0.25	0.5	4.5	15.37	9	2			1.727	0.756	Perforated
0.25	0.5	5	17.08	10	2			1.800	1.242	Perforated
0.25	0.5	5.5	18.79	11	2			1.841	1.735	Perforated
0.25	0.5	6	20.50	12	2			1.867	2.231	Perforated
0.25	0.5	6.5	22.21	13	2			1.885	2.729	Perforated
0.25	0.5	7	23.92	14	2			1.899	3.227	Perforated
0.25	0.5	7.5	25.62	15	2			1.909	3.726	Perforated
0.25	0.5	8	27.33	16	2			1.918	4.225	Perforated
0.25	0.5	0.5	1.71	1	1.75	0.710	1.419	0.000	0.077	
0.25	0.5	1	3.42	2	1.75	1.285	1.285	0.000	0.081	
0.25	0.5	1.5	5.12	3	1.75	1.872	1.248	0.000	0.086	
0.25	0.5	2	6.83	4	1.75	2.476	1.238	0.000	0.090	
0.25	0.5	2.5	8.54	5	1.75	3.121	1.248	0.000	0.092	
0.25	0.5	3	10.25	6	1.75	3.870	1.290	0.000	0.094	
0.25	0.5	3.5	11.96	7	1.75	5.006	1.430	0.000	0.102	
0.25	0.5	4	13.67	8	1.75			0.914	0.178	Perforated
0.25	0.5	4.5	15.37	9	1.75			1.353	0.513	Perforated
0.25	0.5	5	17.08	10	1.75			1.486	0.983	Perforated
0.25	0.5	5.5	18.79	11	1.75			1.548	1.473	Perforated
0.25	0.5	6	20.50	12	1.75			1.584	1.968	Perforated
0.25	0.5	6.5	22.21	13	1.75			1.609	2.466	Perforated
0.25	0.5	7	23.92	14	1.75			1.627	2.964	Perforated
0.25	0.5	7.5	25.62	15	1.75			1.641	3.463	Perforated
0.25	0.5	8	27.33	16	1.75			1.652	3.963	Perforated
0.25	0.5	0.5	1.71	1	1.5	0.589	1.177	0.000	0.090	
0.25	0.5	1	3.42	2	1.5	1.083	1.083	0.000	0.102	
0.25	0.5	1.5	5.12	3	1.5	1.578	1.052	0.000	0.112	
0.25	0.5	2	6.83	4	1.5	2.081	1.040	0.000	0.117	
0.25	0.5	2.5	8.54	5	1.5	2.604	1.041	0.000	0.119	
0.25	0.5	3	10.25	6	1.5	3.167	1.056	0.000	0.120	
0.25	0.5	3.5	11.96	7	1.5	3.815	1.090	0.000	0.121	
0.25	0.5	4	13.67	8	1.5			4.709	1.177	0.000
0.25	0.5	4.5	15.37	9	1.5			0.644	0.225	Perforated
0.25	0.5	5	17.08	10	1.5			1.066	0.564	Perforated
0.25	0.5	5.5	18.79	11	1.5			1.203	1.031	Perforated
0.25	0.5	6	20.50	12	1.5			1.269	1.521	Perforated
0.25	0.5	6.5	22.21	13	1.5			1.310	2.017	Perforated
0.25	0.5	7	23.92	14	1.5			1.337	2.515	Perforated
0.25	0.5	7.5	25.62	15	1.5			1.357	3.014	Perforated
0.25	0.5	8	27.33	16	1.5			1.373	3.514	Perforated

Numerical Assessments

Radius (cm)	Diameter (cm)	Length (cm)	Mass (g)	L/D Ratio	Velocity (km/s)	Depth of Penetration (cm)	P/L Ratio	Residual Velocity (km/s)	Residual Length (cm)	REMARKS
0.125	0.25	0.25	0.21	1	2	0.407	1.628	0.000	0.035	
0.125	0.25	0.5	0.43	2	2	0.716	1.433	0.000	0.035	
0.125	0.25	0.75	0.64	3	2	1.030	1.373	0.000	0.036	
0.125	0.25	1	0.85	4	2	1.343	1.343	0.000	0.037	
0.125	0.25	1.25	1.07	5	2	1.656	1.325	0.000	0.038	
0.125	0.25	1.5	1.28	6	2	1.968	1.312	0.000	0.039	
0.125	0.25	1.75	1.49	7	2	2.281	1.303	0.000	0.040	
0.125	0.25	2	1.71	8	2	2.595	1.297	0.000	0.041	
0.125	0.25	2.25	1.92	9	2	2.919	1.298	0.000	0.042	
0.125	0.25	2.5	2.14	10	2	3.229	1.292	0.000	0.043	
0.125	0.25	3	2.56	12	2	3.896	1.299	0.000	0.044	
0.125	0.25	3.5	2.99	14	2	4.774	1.364	0.000	0.044	
0.125	0.25	4	3.42	16	2			1.410	0.141	Perforated
0.125	0.25	4.5	3.84	18	2			1.724	0.617	Perforated
0.125	0.25	5	4.27	20	2			1.803	1.115	Perforated
0.125	0.25	5.5	4.70	22	2			1.844	1.616	Perforated
0.125	0.25	6	5.12	24	2			1.870	2.117	Perforated
0.125	0.25	6.5	5.55	26	2			1.887	2.618	Perforated
0.125	0.25	7	5.98	28	2			1.901	3.119	Perforated
0.125	0.25	7.5	6.41	30	2			1.911	3.620	Perforated
0.125	0.25	8	6.83	32	2			1.920	4.121	Perforated

0.125	0.25	0.25	0.21	1	1.75			0.000		
0.125	0.25	0.5	0.43	2	1.75			0.000		
0.125	0.25	0.75	0.64	3	1.75			0.000		
0.125	0.25	1	0.85	4	1.75			0.000		
0.125	0.25	1.25	1.07	5	1.75			0.000		
0.125	0.25	1.5	1.28	6	1.75					
0.125	0.25	1.75	1.49	7	1.75					
0.125	0.25	2	1.71	8	1.75					
0.125	0.25	2.25	1.92	9	1.75					
0.125	0.25	2.5	2.14	10	1.75					
0.125	0.25	3	2.56	12	1.75					
0.125	0.25	3.5	2.99	14	1.75					
0.125	0.25	4	3.42	16	1.75					

0.125	0.25	0.25	0.21	1	1.5			0.000		
0.125	0.25	0.5	0.43	2	1.5			0.000		
0.125	0.25	0.75	0.64	3	1.5			0.000		
0.125	0.25	1	0.85	4	1.5			0.000		
0.125	0.25	1.25	1.07	5	1.5					
0.125	0.25	1.5	1.28	6	1.5					
0.125	0.25	1.75	1.49	7	1.5					
0.125	0.25	2	1.71	8	1.5					
0.125	0.25	2.25	1.92	9	1.5					
0.125	0.25	2.5	2.14	10	1.5					
0.125	0.25	3	2.56	12	1.5					
0.125	0.25	3.5	2.99	14	1.5					
0.125	0.25	4	3.42	16	1.5					